

CLAIMS

What is claimed is:

- 5 1. A method for estimating a channel spectrum, the method comprising:
- receiving an input signal from a channel, wherein the input signal includes one or more major echoes and one or more minor echoes, wherein the one or more major echoes and one or more minor echoes are introduced by the channel;
- identifying the one or more major echoes present in the input signal;
- 10 identifying the one or more minor echoes from a filtered autocorrelation function of the input signal in response to a determination that there is only one major echo;
- identifying the one or more minor echoes from a filtered power spectrum of the input signal in response to a determination that there is more than one major echo;
- computing a channel spectrum estimate from the one or more major echoes and the one or more minor echoes; wherein the channel spectrum estimate is usable to remove at least a
- 15 portion of the one or more major echoes and the one or more minor echoes from the input signal.
2. The method of claim 1, further comprising:
- performing a transform on the input signal to produce a spectral representation of the
- 20 input signal;
- wherein said identifying the one or more major echoes and said operations of identifying the one or more minor echoes are performed using the spectral representation of the input signal.
3. The method of claim 2,
- 25 wherein said filtered power spectrum is computed from the spectral representation of the input signal;

wherein said filtered autocorrelation function is computed from the filtered power spectrum.

4. The method of claim 1, wherein said identifying the one or more major echoes
5 comprises analyzing pulses in a signal representing a filtered cross-correlation between a training sequence and a window of the input signal.

5. The method of claim 1, wherein said identifying minor echoes from a filtered autocorrelation function of the input signal comprises:

10 creating a first list of peaks, excluding a peak at zero correlation lag, in the filtered autocorrelation function;

adding a peak from the first list to a second list;

deleting each peak from the first list having a delay time which corresponds to any difference between or sum of delay times of peaks in the first list;

15 repeating said adding and said deleting until the first list is empty, wherein peaks from the first list are added to the second list in order from highest peak amplitude to lowest peak amplitude.

6. The method of claim 1, wherein said identifying minor echoes from a filtered
20 power spectrum of the input signal comprises:

computing a power spectrum F for the major echoes;

(a) subtracting the power spectrum F from the filtered power spectrum of the input signal to obtain a difference spectrum;

(b) computing a stabilized division of the difference spectrum by a conjugate of the
25 power spectrum F;

(c) identifying one or more of the minor echoes from an inverse transform of the stabilized division.

7. The method of claim 6, further comprising:

incorporating the one or more identified minor echoes into the power spectrum of F, and repeating (a), (b) and (c).

5

8. The method of claim 1, further comprising:

multiplying a spectrum of the input signal by a stabilized reciprocal of the channel spectrum to determine a deconvolved spectrum.

inverse transforming the deconvolved spectrum to obtain a time-domain block of
10 samples;

recovering information from the time-domain block of samples.

9. The method of claim 1, wherein the channel is a wireless communication channel.

15 10. The method of claim 1, wherein the channel is a wired communication channel.

11. A method for estimating a channel spectrum, comprising:

receiving an input signal from a channel, wherein the input signal includes one or more echoes introduced by the channel;

20 performing a transform on the input signal to produce a spectral representation of the input signal;

determining the one or more echoes based on the spectral representation of the input signal;

25 computing a channel spectrum estimate from the one or more echoes; wherein the channel spectrum estimate is usable to remove at least a portion of the one or more echoes from the input signal.

12. The method of claim 11, wherein said determining the one or more echoes comprises:

determining one or more major echoes based on the spectral representation of the input signal and a spectral representation of a known training sequence;

5 if there is only one major echo, determining the one or more minor echoes in a first manner based on the spectral representation of the signal;

if there is more than one major echo, determining the one or more minor echoes in a second manner based on the spectral representation of the signal.

10 13. The method of claim 12,

wherein said determining the one or more minor echoes in a first manner comprises determining the one or more minor echoes using a filtered autocorrelation function of the input signal;

15 wherein said determining the one or more minor echoes in a second manner comprises determining the one or more minor echoes using a filtered power spectrum of the input signal;

14. The method of claim 12, wherein said determining the one or more minor echoes in a first manner comprises:

20 computing a filtered autocorrelation function of the input signal from the spectral representation of the input signal;

creating a first list of peaks, excluding a peak at zero correlation lag, in the filtered autocorrelation;

adding a peak from the first list to a second list;

25 deleting each peak from the first list having a delay time which corresponds to any difference between or sum of delay times of peaks in the first list;

repeating said adding and said deleting until the first list is empty, wherein peaks from the first list are added to the second list in order from highest peak amplitude to lowest peak amplitude.

30 15. The method of claim 12, wherein said determining the one or more minor echoes in a second manner comprises:

computing a power spectrum F for the major echoes;

(a) subtracting the power spectrum F from a filtered power spectrum of the input signal to obtain a difference spectrum;

5 (b) computing a stabilized division of the difference spectrum by a conjugate of the power spectrum F ;

(c) identifying one or more of the minor echoes from an inverse transform of the stabilized division.

16. The method of claim 11, further comprising:

10 adjusting the input signal to remove at least a portion of the one or more echoes from the input signal based on the channel spectrum estimate.

17. The method of claim 11,

wherein the input signal is a digital television signal.

15

18. A method for estimating a channel spectrum, comprising:

performing a transform on a signal to produce a spectral representation of the signal;

computing a cross-correlation spectrum by multiplication of the spectral representation of the signal and a spectral representation of a training signal;

20 performing an inverse transform on the cross-correlation spectrum to produce a time-domain cross-correlation function;

computing a first amplitude envelope of the cross-correlation function;

estimating locations of first peaks in the first amplitude envelope that exceed a first amplitude threshold;

25 identifying a first set of major echoes corresponding to the first peak locations from the cross-correlation function;

identifying a reference echo among the first set of major echoes;

if there is only one major echo, then determining minor echoes from a filtered autocorrelation function;

if there is more than one major echo, then determining minor echoes from a filtered power spectrum;

- 5 computing a channel spectrum estimate from the major echoes and minor echoes; wherein the channel spectrum estimate is usable to approximate an original transmission to permit recovery of information from the signal.

19. A method comprising:

- 10 (a) computing a first amplitude envelope of a cross-correlation function;
- (b) estimating locations of first peaks in the first amplitude envelope that exceed a first amplitude threshold;
- (c) identifying from the cross-correlation function a first set of major echoes corresponding to the first peak locations;
- 15 (d) identifying a reference echo among the first set of major echoes;
- (e) executing a first algorithm to determine minor echoes from a filtered autocorrelation function in response to a determination that there is only one major echo;
- (f) executing a second algorithm to determine the minor echoes from a first filtered power spectrum in response to a determination that there is more than one major echo;
- 20 (g) computing a channel spectrum estimate from the major echoes and minor echoes; wherein the channel spectrum estimate is usable to compute an estimate of an original transmission to permit recovery of information from an input signal.

20. The method of claim 19, wherein the first amplitude threshold depends on an estimate of
- 25 a standard deviation of the cross-correlation function in the absence of peaks.

21. The method of claim 19, further comprising: establishing the nearest sample time to the reference echo as the zero-delay reference time for definition of the echo delays.

22. The method of claim 19, wherein the reference echo is an echo having a maximal
5 amplitude among the first set of major echoes;

23. The method of claim 19, wherein execution of the first algorithm includes:
computing a second amplitude envelope of the filtered autocorrelation function;
generating a first list of peaks in the second amplitude envelope, excluding a peak at zero delay,
10 that exceed a second amplitude threshold;
determining the number N_p of peaks in the first list;
sorting the first list according to peak amplitude;
performing a first procedure in response to a determination that the number N_p is greater than or
equal to three, wherein the first procedure includes:
15 (e1) accessing two peaks of largest amplitude from the first list;
(e2) removing the accessed peaks from the first list, and adding delay times and complex
amplitudes corresponding to the accessed peaks to a second list;
(e3) computing a table T of differences between pairs of delay times in the second list,
and computing a table S of sums of pairs of delay times in the second list;
20 (e4) deleting from the first list any peaks whose delay times correspond to at least one of
the generated sums in table S or at least one of the differences in table T;
(e5) accessing a next peak of largest amplitude from the first list, and repeating (e2)
through (e4), in response to a determination that the first list is nonempty;
resolving sign ambiguity of delay times in said second list to determine delay times and
25 corresponding complex coefficients of the minor echoes.

24. The method of claim 23 further comprising performing a second procedure in response to a determination that the number N_p is equal to one, wherein the second procedure includes: adding to the second list the delay time and complex amplitude corresponding to the single peak from the first list.

5

25. The method of claim 23 further comprising performing a third procedure in response to a determination that the number N_p is equal to two, wherein the third procedure includes: adding to the second list the delay times and complex amplitudes corresponding to the two peaks from the first list.

10

26. The method of claim 23, wherein the differences between pairs of delay times in the second list are positive differences.

15 27. The method of claim 23, wherein the differences between pairs of delay times in the second list are negative differences.

28. The method of claim 23, wherein (e4) comprises deleting from the first list any peaks whose delay times correspond within one sample to at least one of the generated sums in table S or at least one of the differences in table T.

20

29. The method of claim 23, wherein said resolving signs comprises:

(e6) generating a vector X of the form (X_1, X_2, \dots, X_M) , wherein M is the number of delay times in the second list, wherein each value X_i equals zero or one;

(e7) computing an echo spectrum estimate according to the expression $T = UV$, where

25
$$U = |A_0| + \sum_{J=1}^M \left(\operatorname{Re}(A_J) + (-1)^{X_J} i \operatorname{Im}(A_J) \right) \exp(2\pi i f d_J (-1)^{X_J}),$$

and

$$V = \exp(2\pi i f d_0) \exp(i \text{Arg}(A_0)),$$

wherein A_J is the complex coefficient associated with the J^{th} echo in the second list,

wherein A_0 is the complex coefficient associated with the reference echo,

5 wherein d_J is the delay time associated with the J^{th} echo in the second list; wherein f is a discrete frequency index;

wherein d_0 is the delay time associated with the reference echo;

(e8) performing a stabilized division of the spectrum of a block B of samples of the input signal by the echo spectrum estimate to obtain an deconvolved signal spectrum, wherein the block B
10 contains a known training sequence;

(e9) inverse transforming the deconvolved spectrum to obtain a deconvolved signal;

(e10) processing the deconvolved signal to decode a sequence of symbols;

(e11) comparing the sequence of decoded symbols with the known training sequence to determine an error;

15 repeating (e6) through (e11) for each of the 2^M states of said vector X;

selecting the echo spectrum estimate corresponding to the state X which minimizes said error as a final echo spectrum estimate.

30. The method of claim 19, wherein execution of the second algorithm includes:

20 (f1) computing a massive spectrum corresponding to a sum of the major echoes;

(f2) computing a filtered power spectrum S_M of the massive spectrum;

(f3) subtracting the filtered power spectrum S_M from the first filtered power spectrum to obtain a difference spectrum;

(f4) performing a stabilized division of the difference spectrum by a conjugate of the massive
25 spectrum to obtain an intermediate spectrum;

(f5) computing an inverse transform of the intermediate spectrum to obtain a time-domain signal;
(f6) identifying peaks of sufficient amplitude in an amplitude envelope of the time-domain signal;
(f7) estimating one or more echoes from the identified peaks and the time-domain signal;
5 (f8) adding the one or more echoes to a list of the minor echoes;
(f9) adding the one or more echoes to the massive spectrum;
(f10) repeating (f2) through (f9) until a termination condition is achieved.

31. The method of claim 30, wherein the termination condition is a condition that the
10 amplitude envelope of the time-domain signal contains no peaks of sufficient amplitude.

32. The method of claim 30, wherein (f2) comprises:
computing a power spectrum P_M of the massive spectrum; and
multiplying the power spectrum P_M of the massive spectrum by a spectral weighting function
15 which takes non-zero values only over non-negative frequencies.

33. The method of claim 19 wherein (c) includes:
(c1) executing an iterative search to minimize a function of the form $f(y-C*A)$ with respect to K
delay times, wherein K is a positive integer, wherein f is an increasing function of distance
20 between y and the matrix-vector product $C*A$, wherein y is the filtered autocorrelation function,
wherein C is a matrix with K columns, wherein the I^{th} column of matrix C represents a copy of a
basis pulse delayed by an I^{th} one of the K delay times; wherein A represents a vector of complex
coefficients;
(c2) comparing a minimized value of the function to a noise level;
25 (c3) increasing the order of the function by incrementing K and repeating (c1) and (c2) if the
minimized value of the function is greater than the noise level;

(c4) storing the minimizing values of the K time delays and a corresponding value of the vector A if the minimized value of the function is less than the noise level.

34. The method of claim 19, wherein (c) includes:

- 5 (c1) executing an iterative search to minimize a function of the form $f(y-L)$ with respect to K delay times, wherein K is a positive integer, wherein f is an increasing function of distance between vector y and a linear combination L, wherein vector y is the filtered autocorrelation function, wherein linear combination L has the form

$$\sum_{I=1}^K C_I * A^I,$$

- 10 where vector C_I represents a copy of a basis pulse delayed by an I^{th} one of the K delay times, wherein A^I is a complex coefficient corresponding to the I^{th} one of the K delay times;

(c2) comparing a minimized value of the function to a noise level;

(c3) increasing the order of the function by incrementing K and repeating (c1) and (c2) if the minimized value of the function is greater than the noise level;

- 15 (c4) storing the minimizing values of the K time delays and a corresponding values of the complex coefficients A^I if the minimized value of the function is less than the noise level.

35. The method of claim 19,

- 20 wherein the cross-correction function represents a cross-correlation between a known training signal and a block of samples of the input signal.

36. The method of claim 19, further comprising:

averaging a first stream of power spectra of the input signal to obtain a second stream of averaged power spectra;

multiplying each averaged power spectrum of the second stream by a spectral weighting function defined over positive frequencies to obtain a third stream of filtered power spectra of the input signal;

wherein said first filtered power spectrum is a current one of the filtered power spectra in the
5 third stream;

wherein the filtered autocorrelation function results from an inverse transform of the first filtered power spectrum.

37. The method of claim 36, wherein the weighting function is a non-negative real symmetric
10 spectrum whose decay at high frequencies is such that the amplitude envelope of the corresponding analytic signal in the time domain has a single maximum.

38. A method comprising:

- (a) receiving a first stream of blocks of samples of an input signal;
- 15 (b) computing a transform of each block of samples to generate a second stream of signal spectra;
- (c) performing a frequency-domain autocorrelation operation on each signal spectrum of the second stream to obtain a third stream of power spectra;
- (d) filtering the third stream of power spectra to obtain a fourth stream of filtered power spectra;
- 20 (e) computing an analytic signal S_A by performing an inverse transform of a current one of the fourth stream of filtered power spectra over non-negative frequencies;
- (f) estimating complex coefficients for a set of echoes from an analysis of pulses in selected intervals of the analytic signal S_A , given a current estimate of delay times for the set of echoes;
- (g) generating a revised channel spectrum estimate from phase changes of the estimated complex
25 coefficients and the current estimate of the delay times;
- (h) repeating (e), (f), and (g);
- (i) updating the set of echoes including delay times in response to an update condition.

39. The method of claim 38, wherein the update condition is a condition indicating that one or more of the delay times of the set of echoes have detectably changed since a last update.

5 40. The method of claim 38, wherein said repeating comprises repeating (e), (f) and (g) at a rate determined by a largest time rate of change of the phases of the estimated complex coefficients.

41. The method of claim 38, wherein said analysis of pulses in an interval X of said selected
10 intervals comprises computing an estimate A for a vector of the form

$$(C^{*T}C)^{-1}C^{*T}y,$$

wherein y is the analytic signal S_A , wherein each column of matrix C is a copy of a basis pulse shifted in time by an amount equal to the current estimate of delay time, of an echo in said set of echoes, occurring in the interval X, wherein components of the vector A are the estimates of the
15 complex coefficients of the echoes occurring in the interval X.

42. The method of claim 38 wherein the selected intervals are intervals containing pulses of sufficient amplitude in the amplitude envelope of analytic signal S_A .

20 43. The method of claim 38, wherein said filtering comprises performing an IIR filtration on the third stream of power spectra to obtain the fourth stream of filtered power spectra.

44. The method of claim 43, wherein a recursion coefficient α of the IIR filtration is determined by said largest time rate of change of the phases of the estimated complex
25 coefficients.

45. A method for estimating a channel spectrum, the method comprising:

averaging a first stream of power spectra of an input signal to generate a second stream of averaged power spectra;

filtering a selected one of the averaged power spectra in the second stream to obtain a filtered
5 power spectrum;

computing an inverse transform on the filtered power spectrum to obtain an autocorrelation signal;

analyzing peaks in the autocorrelation signal to determine a significant subset of the peaks;

computing echo delay times and echo coefficients from the significant subset of the peaks;

10 computing a channel spectrum estimate from the echo delay times and echo coefficients;

wherein the channel spectrum estimate is usable to compute an estimate of an original transmission to permit recovery of information from the input signal.

46. The method of claim 45 further comprising:

15 performing a frequency-domain deconvolution operation on one or more signal spectra of the input signal using the channel spectrum estimate to obtain one or more corresponding deconvolved spectra;

computing an inverse transform of each of the deconvolved spectra to obtain deconvolved blocks of samples; and

20 recovering information from the deconvolved blocks of samples.

47. The method of claim 46, wherein the frequency-domain deconvolution is a stabilized deconvolution.

25 48. The method of claim 45, wherein said averaging comprises averaging with an IIR filter, such that the effect of past contributions to the average decays exponentially with time.

49. A signal receiver system, comprising:

a memory configured to store program instructions; and

a processor configured to read and execute program instructions from the memory,

5 wherein, in response to execution of said program instructions, the processor is operable to:

receive an input signal from a channel, wherein the input signal includes one or more major echoes and one or more minor echoes, wherein the one or more major echoes and one or more minor echoes are introduced by the channel;

identify the one or more major echoes present in the input signal;

10 identify the one or more minor echoes from a filtered autocorrelation function of the input signal in response to a determination that there is only one major echo;

identify the one or more minor echoes from a filtered power spectrum of the input signal in response to a determination that there is more than one major echo; and

15 compute a channel spectrum estimate from the one or more major echoes and the one or more minor echoes; wherein the channel spectrum estimate is usable to remove at least a portion of the one or more major echoes and the one or more minor echoes from the input signal.

50. A signal receiver system, comprising:

20 an input for receiving an input signal from a channel, wherein the input signal includes one or more major echoes and one or more minor echoes, wherein the one or more major echoes and one or more minor echoes are introduced by the channel;

means for identifying the one or more major echoes present in the input signal;

25 means for identifying the one or more minor echoes from a filtered autocorrelation function of the input signal in response to a determination that there is only one major echo;

means for identifying the one or more minor echoes from a filtered power spectrum of the input signal in response to a determination that there is more than one major echo;

means for computing a channel spectrum estimate from the one or more major echoes and the one or more minor echoes; wherein the channel spectrum estimate is usable to remove at least a portion of the one or more major echoes and the one or more minor echoes from the input signal.

5

51. A memory medium comprising program instructions for estimating a channel spectrum, wherein the program instructions are executable to implement:

receiving an input signal from a channel, wherein the input signal includes one or more major echoes and one or more minor echoes, wherein the one or more major echoes and one or
10 more minor echoes are introduced by the channel;

identifying the one or more major echoes present in the input signal;

identifying the one or more minor echoes from a filtered autocorrelation function of the input signal in response to a determination that there is only one major echo;

identifying the one or more minor echoes from a filtered power spectrum of the input
15 signal in response to a determination that there is more than one major echo;

computing a channel spectrum estimate from the one or more major echoes and the one or more minor echoes; wherein the channel spectrum estimate is usable to remove at least a portion of the one or more major echoes and the one or more minor echoes from the input signal.

20 52. A method for determining a set of minor echoes from an input signal, the method comprising:

receiving the input signal;

determining that there is more than one major echo in the input signal;

(a) computing a spectrum F corresponding to a sum of the major echoes;

25 (b) computing a filtered power spectrum S_M of the spectrum F ;

(c) subtracting the filtered power spectrum S_M from a filtered power spectrum of the input signal to obtain a difference spectrum;

(d) performing a stabilized division of the difference spectrum by a conjugate of the spectrum F to obtain an intermediate spectrum;

(e) computing an inverse transform of the intermediate spectrum to obtain a time-domain signal;

5 (f) estimating one or more of the minor echoes from the time-domain signal;

(g) adding the one or more estimated echoes to the spectrum F.

53. The method of claim 52, further comprising:

repeating (b) through (g) until a termination condition is achieved.

10

54. A method for determining minor echoes from an input signal, the method comprising:

receiving the input signal;

determining that there is only one major echo in the input signal;

15 computing an amplitude envelope of a filtered autocorrelation function of the input signal;

generating a first list of peaks in the amplitude envelope, excluding a peak at zero delay, that exceed an amplitude threshold;

determining the number N_P of peaks in the first list;

20 performing a first procedure in response to a determination that the number N_P is greater than or equal to three, wherein the first procedure includes:

(a) accessing two peaks of largest amplitude from the first list;

(b) removing the accessed peaks from the first list, and adding delay times and complex amplitudes corresponding to the accessed peaks to a second list;

25 (c) computing a table T of differences between pairs of delay times in the second list, and computing a table S of sums of pairs of delay times of the accepted peaks;

(d) deleting from the first list any peaks whose delay times correspond to at least one of the generated sums in table S or at least one of the differences in table T;

(e) accessing a next peak of largest amplitude from the first list, and repeating (b) through (d), in response to a determination that the first list is nonempty.

5

55. The method of claim 54, further comprising:

resolving sign ambiguity of time delays in said second list to determine time delays and corresponding complex coefficients of the minor echoes.

10

56. The method of claim 54 further comprising: sorting the first list according to peak amplitude prior to said performing the first procedure.

15